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EQUIPMENT TO SUPPORT THE DEVELOPMENT OF HIGH RESOLUTION GEOPHYSICAL SITE CHARACTERIZATION PROCEDURES

FINAL REPORT ON INSTRUMENTATION
AFOSR-89-0121
13 FEB 90

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An important application of high resolution geophysical exploration is to the interpretation of strong ground motions from chemical and nuclear explosions. High dynamic range data acquisition systems which are capable of acquiring multiple channels of data are necessary. Ground motion sensors, data analysis microsystem, and field enclosures were supported under this grant. Spanning ground motions from the low level exploration environment to the strong levels next to explosive sources was done with a collection of geophones, seismometers, and accelerometers. Four applications of the new system in a range of experiments from quantification of near-source ground motions from a contained nuclear explosion to the characterization of a new AFOSR supported shear wave generator are given.

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ABSTRACT

Under the current AFOSR Grant (AFOSR-89-0176) new near-surface geologic site characterization procedures have been under development. These tools separate *stochastic and deterministic* properties of near surface materials (Stump, 1987; Stump, 1989a). They have most recently been extended to include new instrument array designs, data acquisition techniques, and high resolution frequency-wavenumber analysis (Stump, 1989b). Geophysical exploration tools are important to the Air Force in estimating risk to near-surface structures from explosive loading either nuclear or non-nuclear. The most recent work involves the development OF shear wave sources and associated exploration techniques which will further refine our understanding of near-surface geological materials.

An important application of these geophysical exploration techniques is to the interpretation of strong ground motion from chemical and nuclear explosions (Reinke et al., 1989; Stump, Bogaards, and Reinke, 1988). The threat of a spatially incoherent motion field on an engineering structure such as a missile silo can be significantly different from a coherent one. The new exploration techniques allow the inclusion of stochastic wave propagation effects in the analysis.

The new site characterization tools require high dynamic range data acquisition systems which are capable of acquiring multiple data channels simultaneously. The data must also be accessible in the field for preliminary analysis and quality checks. Since the goal of our work is to correlate site exploration information with waveforms generated from more energetic explosive blasts, a number of different sensors must be available to cover a large range of ground motion environments. The recording system for these experiments was acquired under the support of DARPA and consists of 10 Refraction Technology Digital Acquisition Systems (DASs) each capable of retrieving 6 channels of data at data rates as high as 1000 samples/s (Figure 1).

Ground motion sensors, data analysis microsystem, and field enclosure were supported under the AFOSR Grant (AFOSR-89-0121). Spanning the ground motions from the low level exploration environment to the strong levels next to explosive sources was done with a collection of geophones, seismometers, and accelerometers. With the acquisition of this new equipment we can now do geophysical exploration as well as monitor high stress motions from explosions with the same system.

Four applications of the new system in a range of experiments from quantification of near-source ground motions from a contained nuclear explosion (DARPA/AFGL F19628-89-K-0025) to the characterization of our new AFOSR supported shear wave generator (AFOSR-89-0176) will be given.

EQUIPMENT

The design goal of this data acquisition system was to develop a single system that could be used in geophysical site characterization which involves very small levels of ground motion as well as in recording strong ground motions from close to explosions. The site characterization data are used to estimate variations in ground motions from explosive loading. The material property estimates from the geophysical exploration tools are validated or tested by recording the strong ground motions from explosive sources.

Near-source explosion characterization is not only important to estimating risk to Air Force structures, but these studies can lead to a phenomenologically based understanding of seismic energy coupling from explosions. This understanding is fundamental to quantification of discrimination and verification issues associated with underground nuclear testing and treaties. The same instruments that are being used for the shallow site characterization work are utilized under a DARPA sponsored project (DARPA/AFGL F19628-89-K-0025). This work is designed to: (1) Quantify ground motions from quarrying operations; (2) Investigate near-source ground motion contributions from spall, the tensile failure of near-surface materials above a contained explosion; and (3) Compare and contrast free-surface and free-field (subsurface) ground motions from nuclear explosions. The digital acquisition system was supported by DARPA while the sensors, analysis microsystem, and instrument enclosure was sponsored by AFOSR.

Our approach to instrumenting ground motions over the range of levels expected from the energetic explosive to the weak exploration sources was to acquire three levels of ground motion sensors. The first were a set of force-balance accelerometers which could be used in capturing motions close to explosive sources. Terra Technology was the manufacturer of the 10 three-component (3 orthogonal axis) accelerometers. These instruments were chosen primarily because of the field rangeable levels from 0.1 to 10 *g's* in peak acceleration.

At the intermediate motion levels for recording explosion sources we chose the three component velocity seismometers of Sprengnether Instruments, Inc, S-6000. The instruments are known for economical packaging, reliability, and ruggedness. Their natural frequency of 2 Hz and transducer constant of 12.5 v/m/s makes them particularly suited for our explosive studies. These seismometers coupled with the sixteen bit data acquisition system allow us to transition from the near-source region (1-10 km) to regional distances (100's km) in our explosion studies.

The final set of seismic instruments were a set of vertical and horizontal geophones designed for use in our exploration studies (Figure 2). The goal in

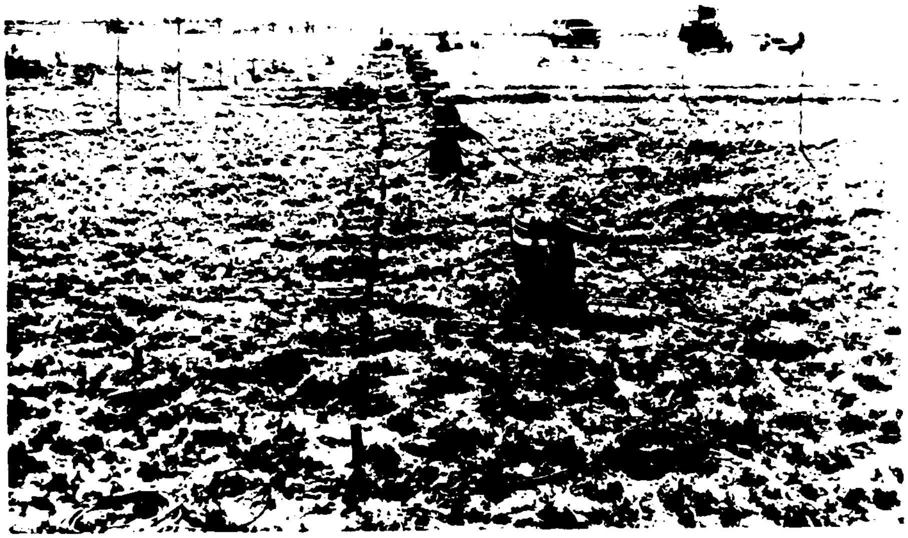


Figure 1a: Linear array of DASs and geophones from the Oct 89 site characterization at McCormick Ranch, NM. The data acquisition vehicle is seen in the upper right hand corner. All data is telemetered to a central data controller at that location.

Figure 1b: Circular array of DASs and geophones from the Jan 90 shear wave generator tests at McKinney, Texas. The technician to the left is setting up one of the DASs while the student to the right is installing one of the geophones.

Figure 2a: One of the Mark Products L-410, 10 Hz, horizontal geophones.

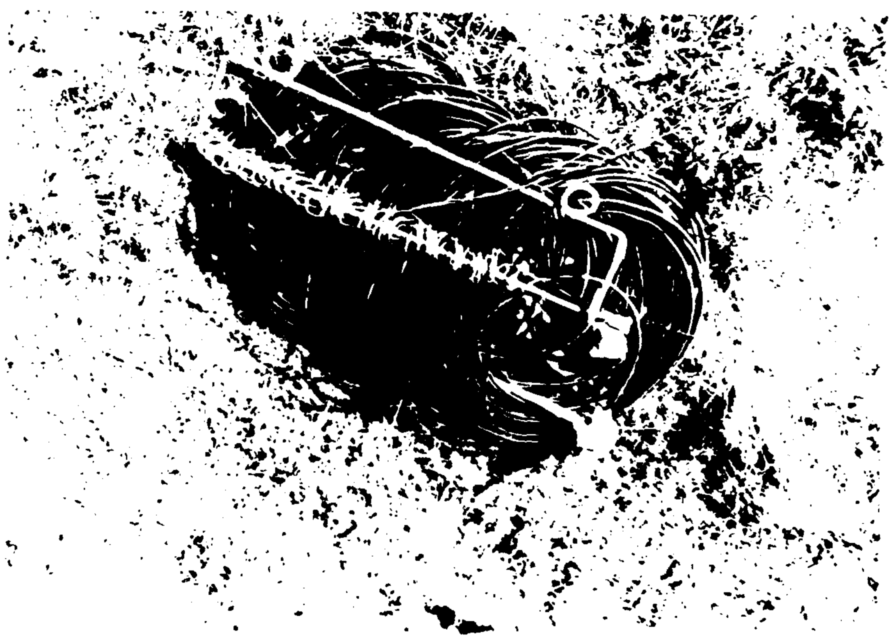


Figure 2b: Clapse containing a number of geophones and connectors.

the exploration work is to densely sample the wavefield so the transition from one propagation regime to another can be identified. With this need in mind 75 vertical and horizontal (each single component) geophones were purchased. The vertical geophones will be used in high resolution frequency-wavenumber studies as well as separation of stochastic and deterministic wave propagation effects (Stump, 1989b) while the horizontal instruments will allow us to utilize our new shear wave techniques. The particular geophones we purchased were built by Mark Products, Inc., L-410, 10 Hz with 0.60 damping.

The instrument enclosure (Figure 3) was designed to include power for operating the seismic system as well as compressed air to drive our shear wave exploration source. The enclosure is intended to give us a place to complete preliminary data analysis in the field. It was built to our specifications by P&S Camper Manufacturing Inc with the power supplied by a Honda EM 5000SX and compressed air by Granger, Inc. The winch for moving equipment was supplied by United Fleet Equipment, Inc.

The final piece of the system was seismic test and analysis microsystem. This piece of equipment was designed to give us a quick look data analysis system which was compatible with the data acquisition systems as well as our equipment in the laboratory. A Sun 386i/250 was chosen since it can simultaneously function under the DOS operating system which is compatible with our field data acquisition system (Figure 4) and UNIX which is compatible with our laboratory system. We see this microsystem as a bridge between these two environments.

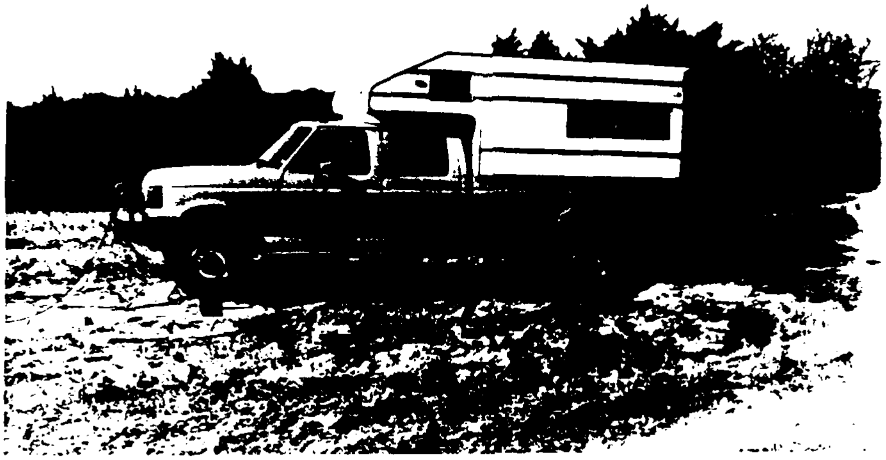


Figure 3: Data acquisition vehicle with equipment enclosure. The front wheels of the vehicle are resting on the shear wave generator. This configuration is standard during data acquisition.

Figure 4: Field computer and radio telemetery system for acquiring data from all 10 DASs over a radio link

EQUIPMENT	ESTIMATED COST	ACTUAL COST
3 Component Terra Technology Force-Balance Accelerometers (10)	$40,000	$37,918.30
Connectors/Batteries	$1,500	$459.95
3 Component Sprengnether Velocity Gages (10)	$15,000	$19,112.13
75 Vertical/Horizontal Geophones with Cables	$12,000	$9632.00
Seismic Test and Analysis Microsystem	$18,392	$18,506
Instrument Enclosures/Mounting	$4233	$4406.55
Bumper Winch	$1375	$1678
TOTAL	$92,500	$91,712.93

PROGRESS

In this final section we will illustrate the flexibility of the new recording system and instrumentation purchased under this contrast. Four separate experiments will be discussed including a contained nuclear explosion (DARPA/AFGL F19628-89-K-0025), a high yield surface explosion (chemical) (DARPA/AFGL F19628-89-K-0025), a test of our new shear wave source (AFOSR-89-0176), and a shallow P/S site characterization (AFOSR-89-0176). The goal of our instrumentation development was to build a single system that could be used for both site exploration and characterizing large explosive sources. These experiments illustrate that the goal has been reached.

A set of experiments have been designed in cooperation with DARPA, Defense Nuclear Agency (DNA), and Los Alamos National Laboratory (LANL) to document the transition from nonlinear to linear ground motion around several nuclear explosions. The DNA tunnel experiments MISTY ECHO and MINERAL QUARRY at the Nevada Test Site have been chosen for these studies. MISTY ECHO was conducted in the last year (Stump et al, 1989) while MINERAL QUARRY is planned for the coming months. The Terra Technology force-balance accelerometers in conjunction with the Refraction Technology DASs were deployed on the free surface above the explosion while additional gages were grouted at shot level and recorded underground (free-field) motions. In addition to the motion measurements, CORRTEX is planned for MINERAL QUARRY. The purpose of these experiments is to compare free-field and free surface data in addition to constraining important physical effects in the source region observed in the radiated seismic waves. Figure 5 is the instrumentation array deployed for Misty Echo while Figure 6 contains a comparison of peak radial acceleration between free-field and free surface observations. This and other data indicate a marked increase in scatter of free surface data contrasted against free-field data. Free surface data may be reflecting lateral variations in the weathered zone where the instruments are placed. Free-field data may be more representative of the source.

In June we deployed two small arrays, 90 m total linear dimension, around the MISER'S GOLD surface explosion at White Sands Missile Range. This test which was sponsored by DNA consisted of 2 kilotons of chemical explosive detonated at the surface. The seismic arrays consisted of 6 three-component S-6000's recorded by the Refraction Technology DASs. This deployment was designed to test the new velocity instruments as well as the coherence of free surface observations at near-regional distances. Six radial velocity records from one array site are reproduced in Figure 7a. An overlay of 6 seconds of the P wave is given in Figure 7b illustrating subtle differences across the array. These differences are quantified by the coherence estimates in Figure 8. Here we see that at close station spacing , 3 m, the coherence remains high to frequencies as great as 20 Hz. The frequency band of high coherence decreases

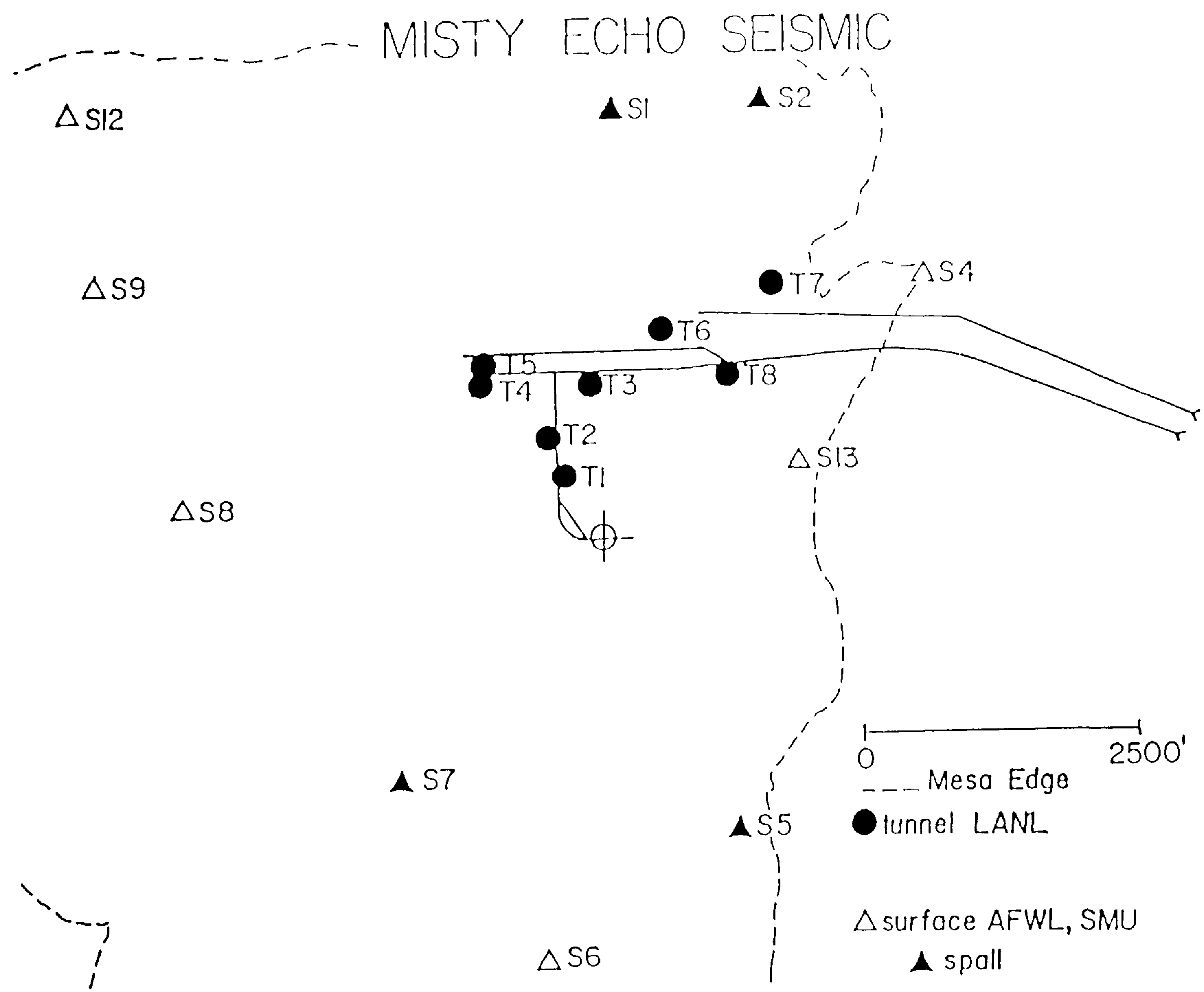


Figure 5 Plan-view of the combined free surface and free-field arrays for the MISTY ECHO experiment.

MISTY ECHO FF AND FS DATA

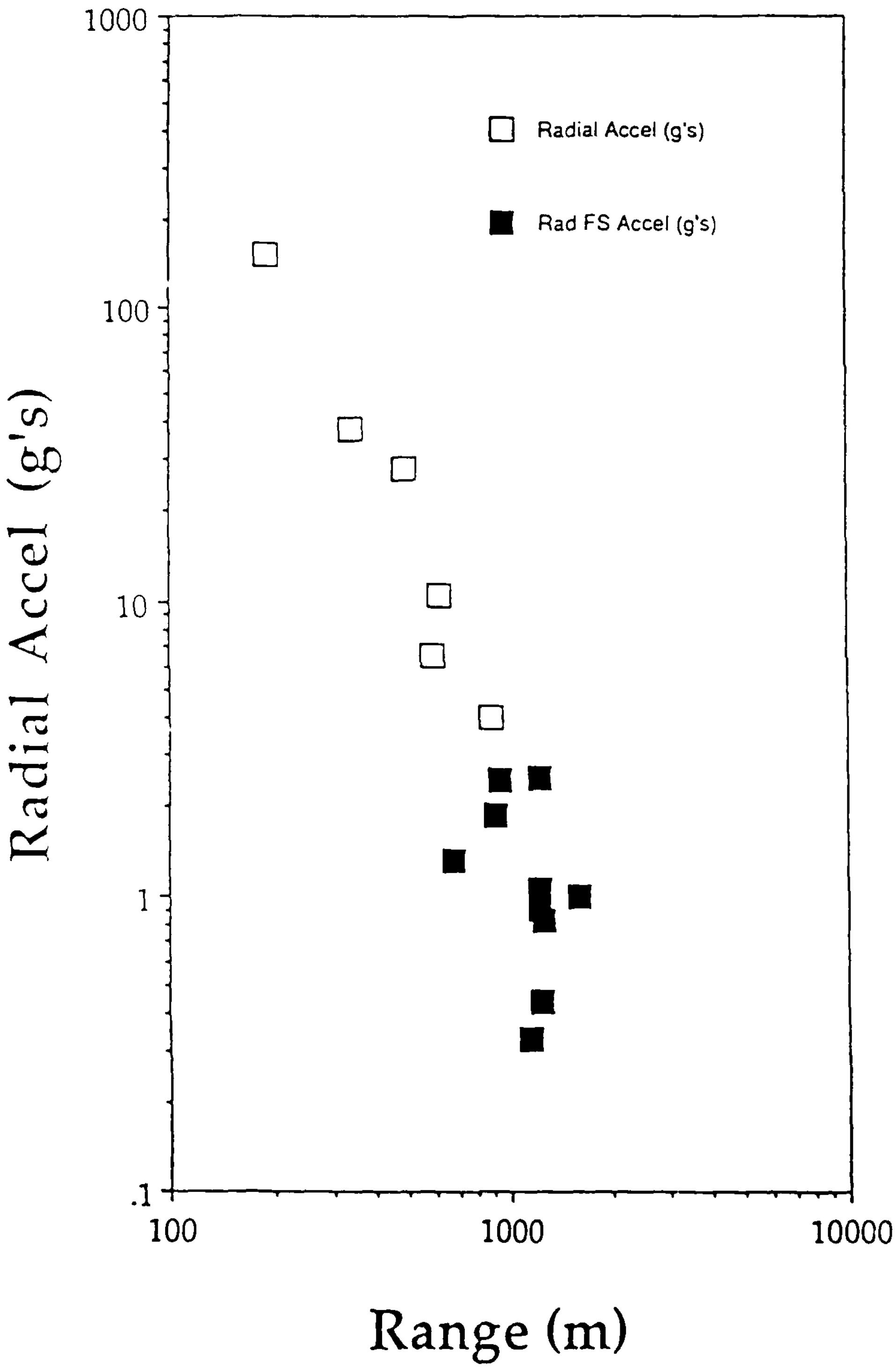


Figure 6 Free-field (open squares) and free surface (closed squares) peak radial accelerations from MISTY ECHO.

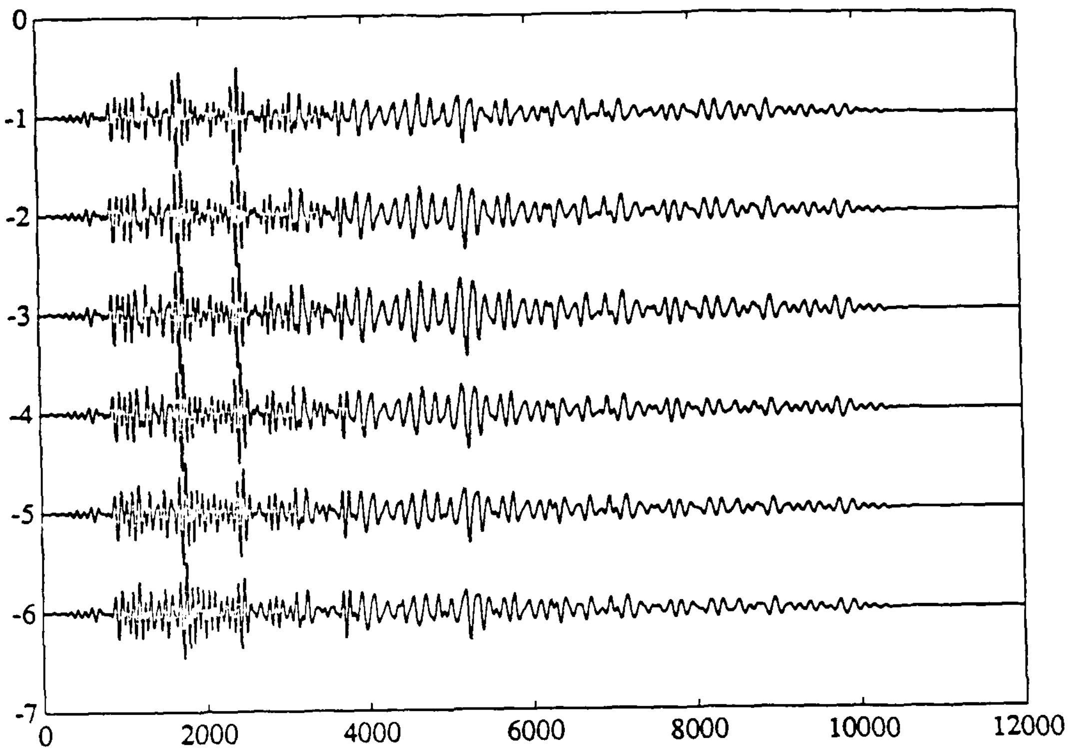


Figure 7a: Radial velocities from the MISER'S GOLD explosion at White Sands Missile Range. 60 seconds of data are displayed. The station separation is 1-2: 3m, 1-3: 12m, 1-4: 17m, 1-5: 50m, 1-6: 90m. The S-6000 velocity instruments were used.

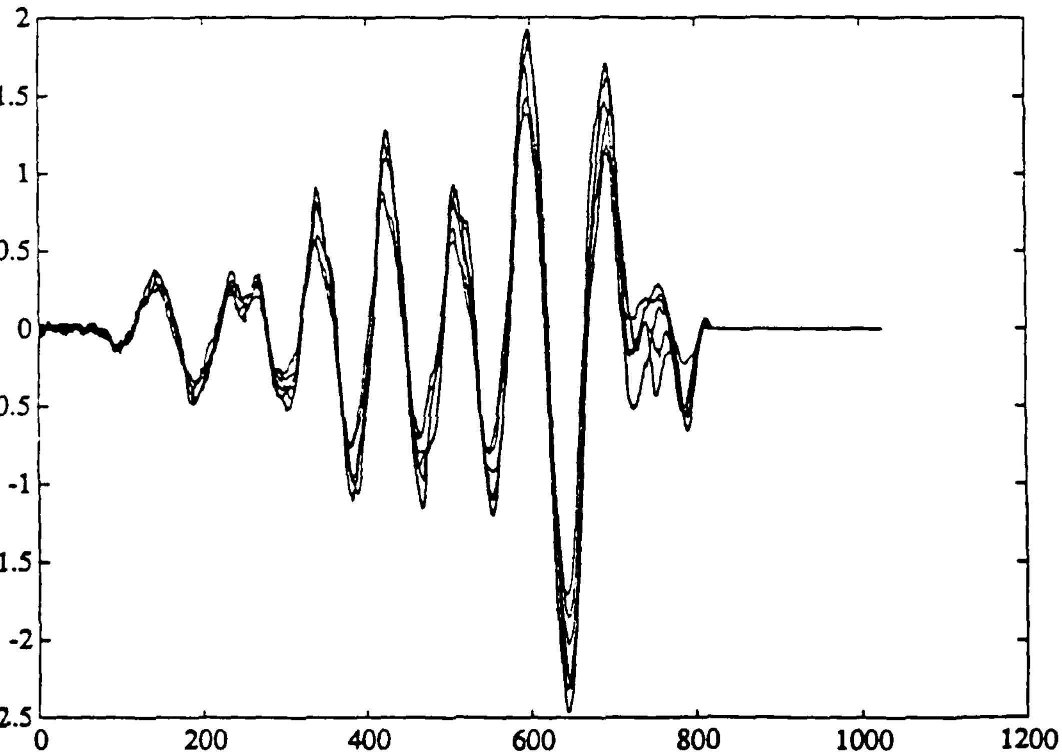
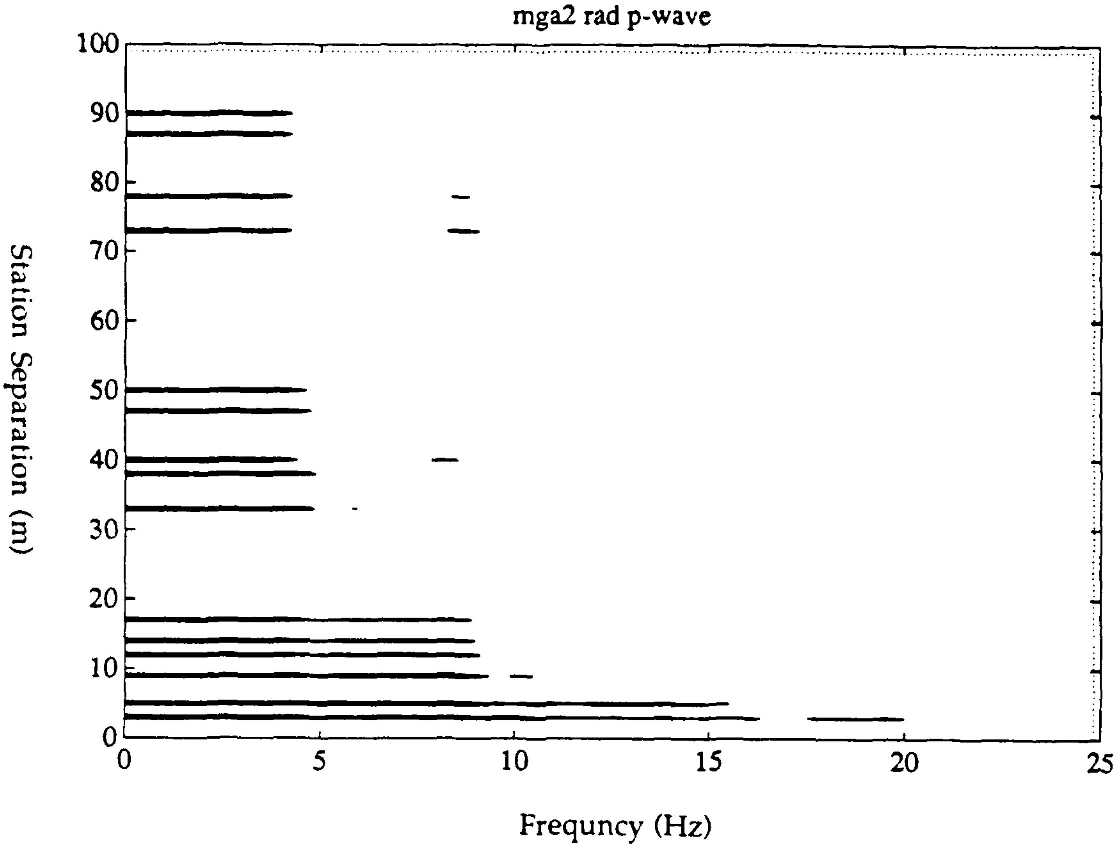


Figure 7b: An overlay of the radial P waves from the 6 records in Figure 7a. Six seconds of data are displayed.



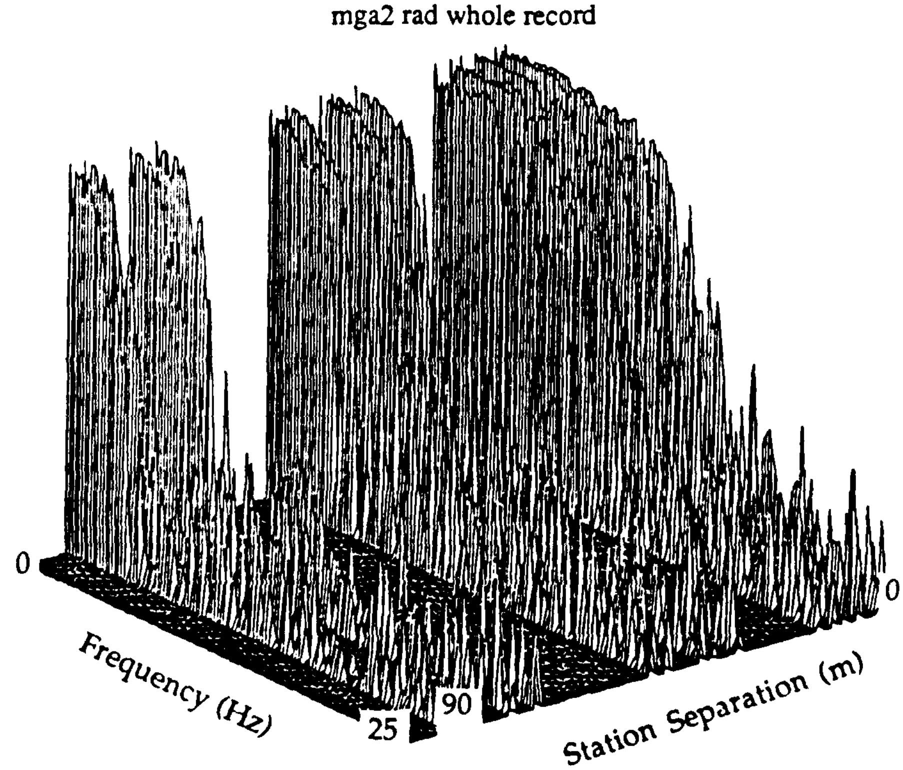


Figure 8a and b: Coherence as a function of station separation for the data in Figure 7a. In 8a only coherence values above 0.7 are displayed. The 3 dimensional plot in 8b displays all coherence values.

with increasing interstation spacing to as little as 7 Hz for station spacings of 70-90 m. These data and their analysis illustrate the impact of near surface material properties on regional observations. The lack of high frequency coherence in these data suggest that high frequency regional observations may be dominated by near surface material effects and not source information.

In October we completed our first site characterization with the new instrumentation. The site chosen for study was the McCormick Ranch Test Site operated by the Air Force Weapons Laboratory in Albuquerque, New Mexico. The purpose of this study was not only to test the exploration geophones with the data acquisition system but was to contrast our new shear wave generator against the Betsy Seisgun compressional wave source. These site characterization studies are designed to utilize the complete wavefield, body and surface waves, in constraining near surface material properties. High dynamic range data is a necessity in recovering both surface and body wave data. A linear array of instruments (Figure 1a) was deployed. Figure 9a is the seismic record section recovered with the new geophones using the Betsy Seisgun. The initial P waves followed by the dispersive surface waves are easily identified in the record section between 1 and 60 m. The shear wave section is given in Figure 9b and can be overlayed with the P section with the supplied overlay. The presence of shear waves is verified by reversing the polarity of the source which led to the section in Figure 9c. This section can be overlayed with that in 9b to emphasize the shear waves which are 180^{o} out of phase for the two source polarities. This new shear wave source looks to be an excellent shallow site characterization tool which when used in combination with standard P wave sources will make a complete characterization of shallow geological material properties possible.

The final set of tests were conducted in January to characterize the spatial and temporal characteristics of the new shear wave generator. In this case a circular array consisting of 60 vertical and 60 horizontal geophones were deployed around the source (Figure 1b). Our earlier tests confirmed the generation of strong shear waves (Figure 9). These final trials were designed to contrast the azimuthal variation of the shear wave generator with that of the Betsy Seisgun. The geophones were spaced at 6^{o} increments at a range of 20m. Azimuthal record sections for the Betsy and shear wave sources are given in Figures 10a and b. In order to quantify the azimuthal variations in the waveforms a polar plot which bounded peak amplitudes for each source orientation were made and included in the top panel of each plot. In absolute amplitude the shear wave generator (Figure 10b) yields transverse velocities which are 2-3 times larger than the vertical motions from the Betsy (Figure 10a). The Betsy amplitudes although exhibiting some scatter with azimuth fill almost all quadrants with equal energy. The shear wave data is roughly dipolar with energy confined to lobes to the north and southwest. The shear wave generator was aligned east-west in these trials and so a north-south

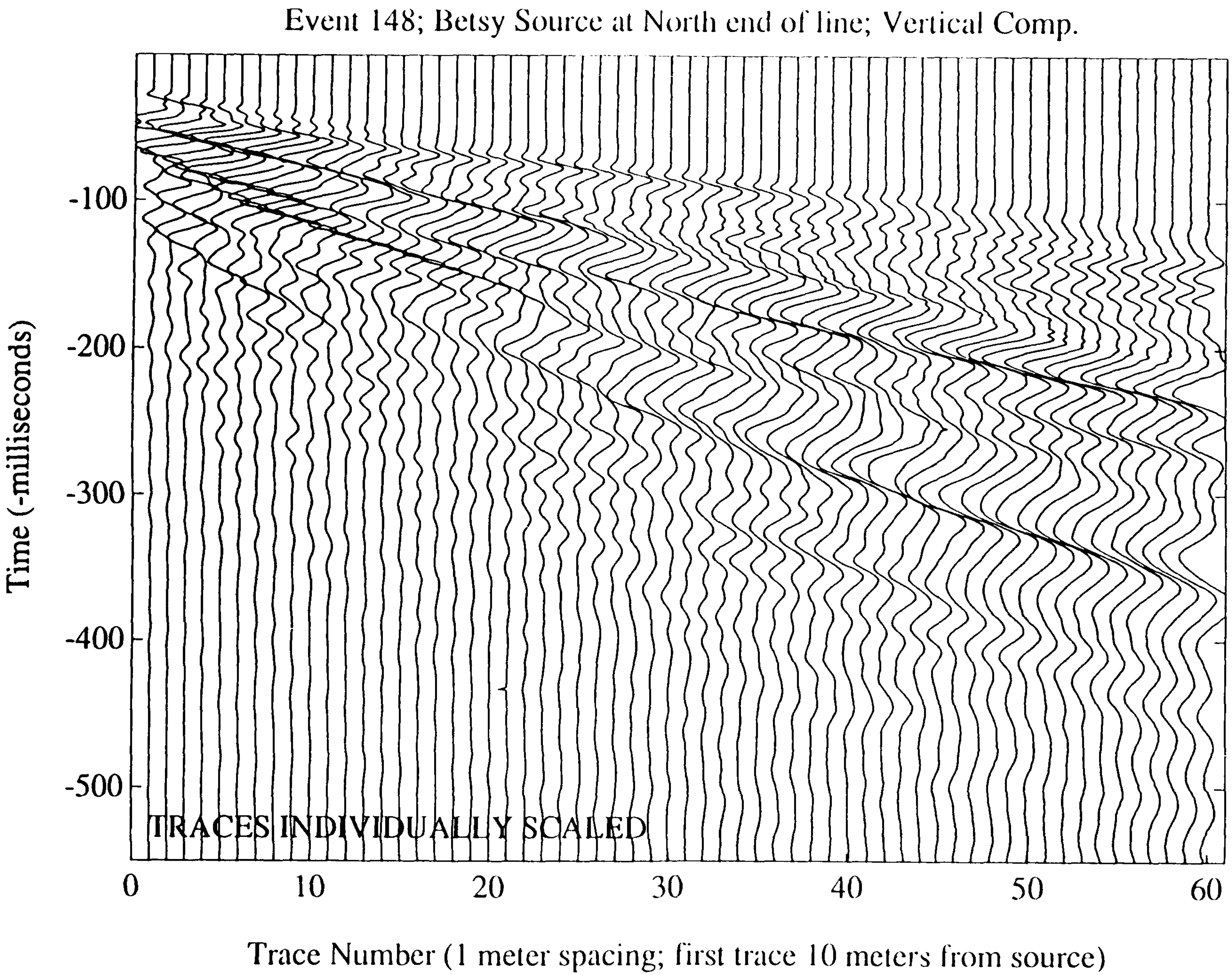

Event 148; Betsy Source at North end of line; Vertical Comp.
Time (-milliseconds)
-100
-200
-300
-400
-500
TRACES INDIVIDUALLY SCALED
0
10
20
30
40
50
60
Trace Number (1 meter spacing; first trace 10 meters from source)

Figure 9a

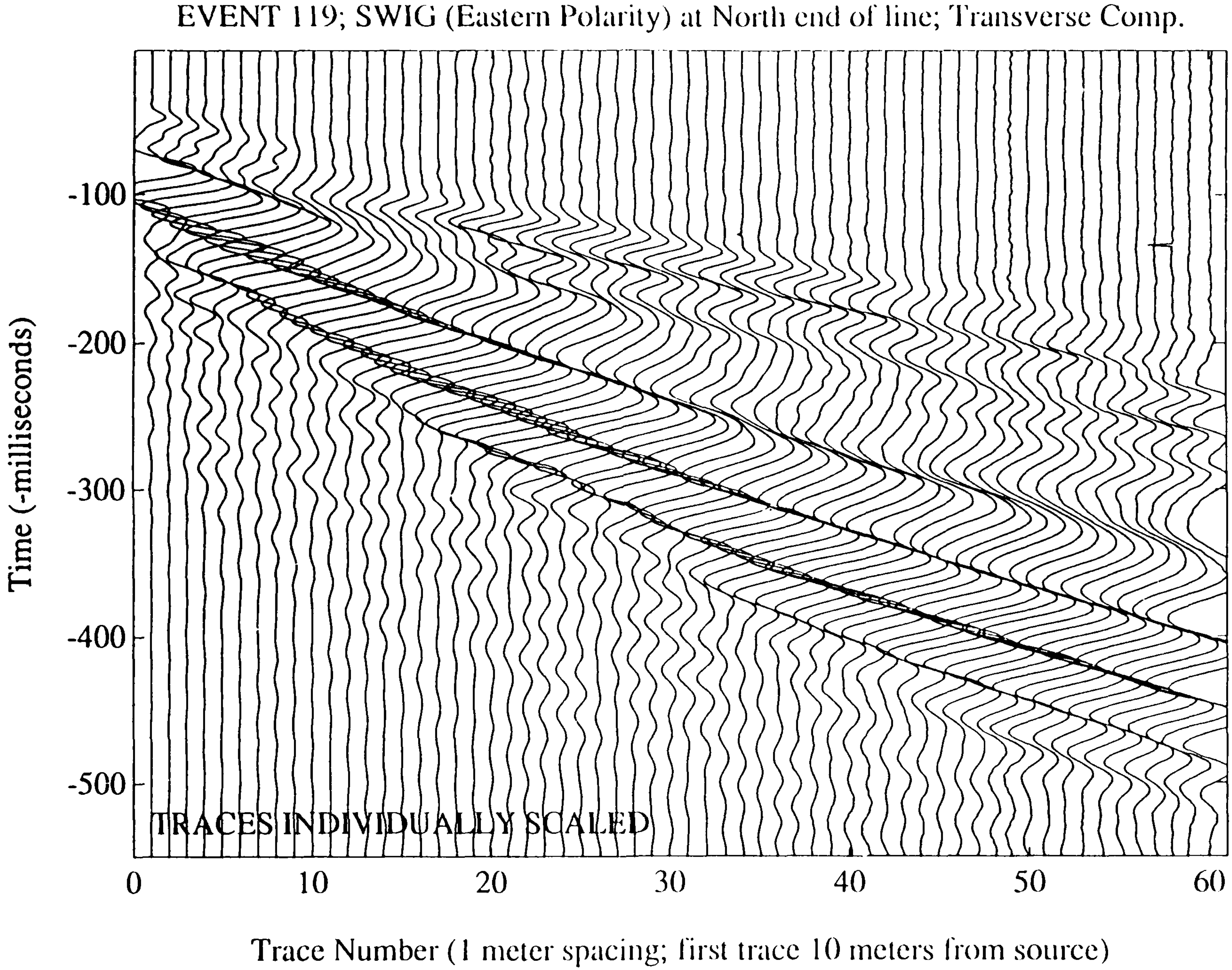

EVENT 119; SWIG (Eastern Polarity) at North end of line; Transverse Comp.
Time (-milliseconds)
-100
-200
-300
-400
-500
TRACES INDIVIDUALLY SCALED
0
10
20
30
40
50
60
Trace Number (1 meter spacing; first trace 10 meters from source)

Figure 9b

Event 120; SWIG (Western Polarity) at North end of line; Transverse Comp.

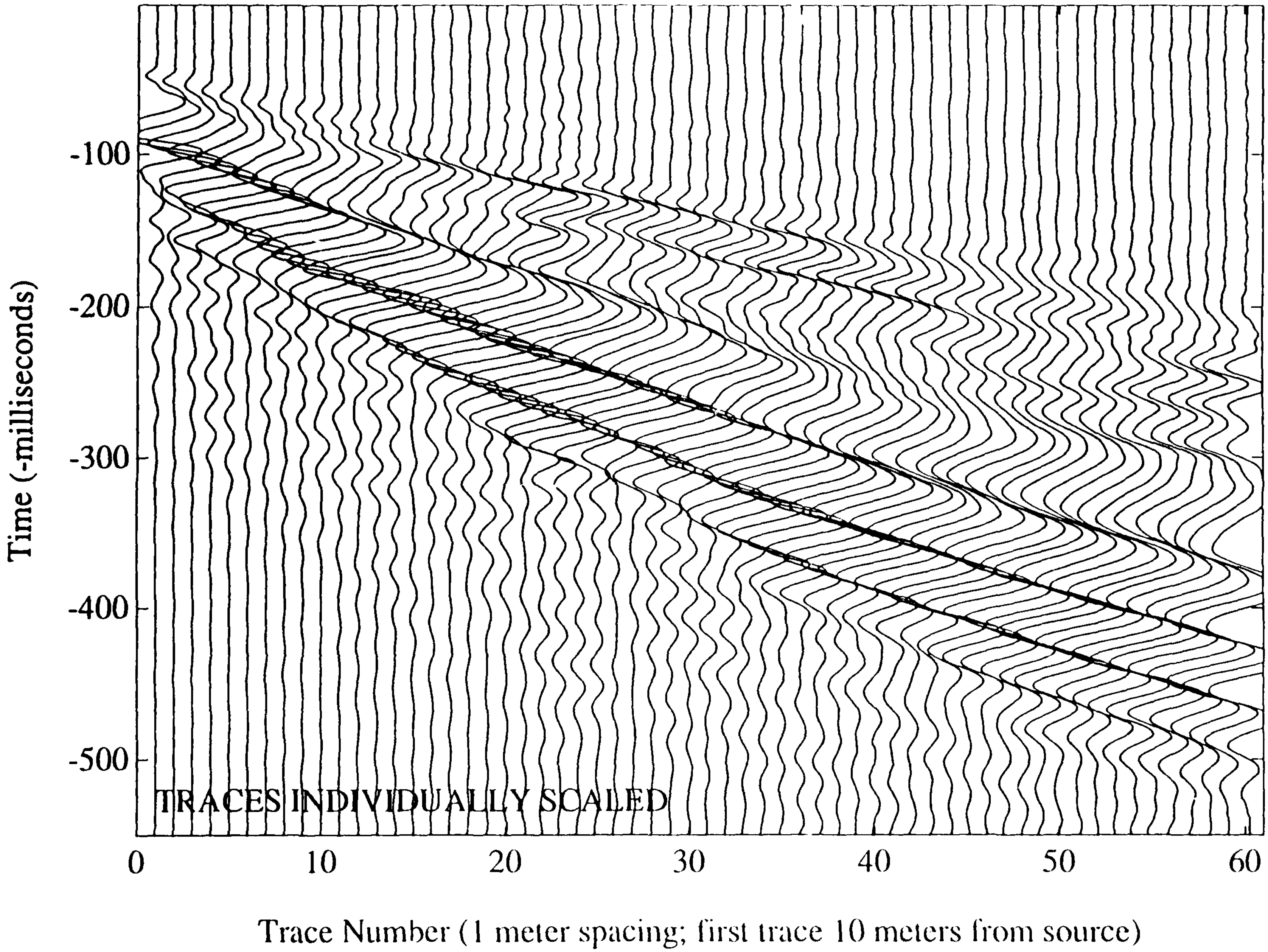


Figure 9c

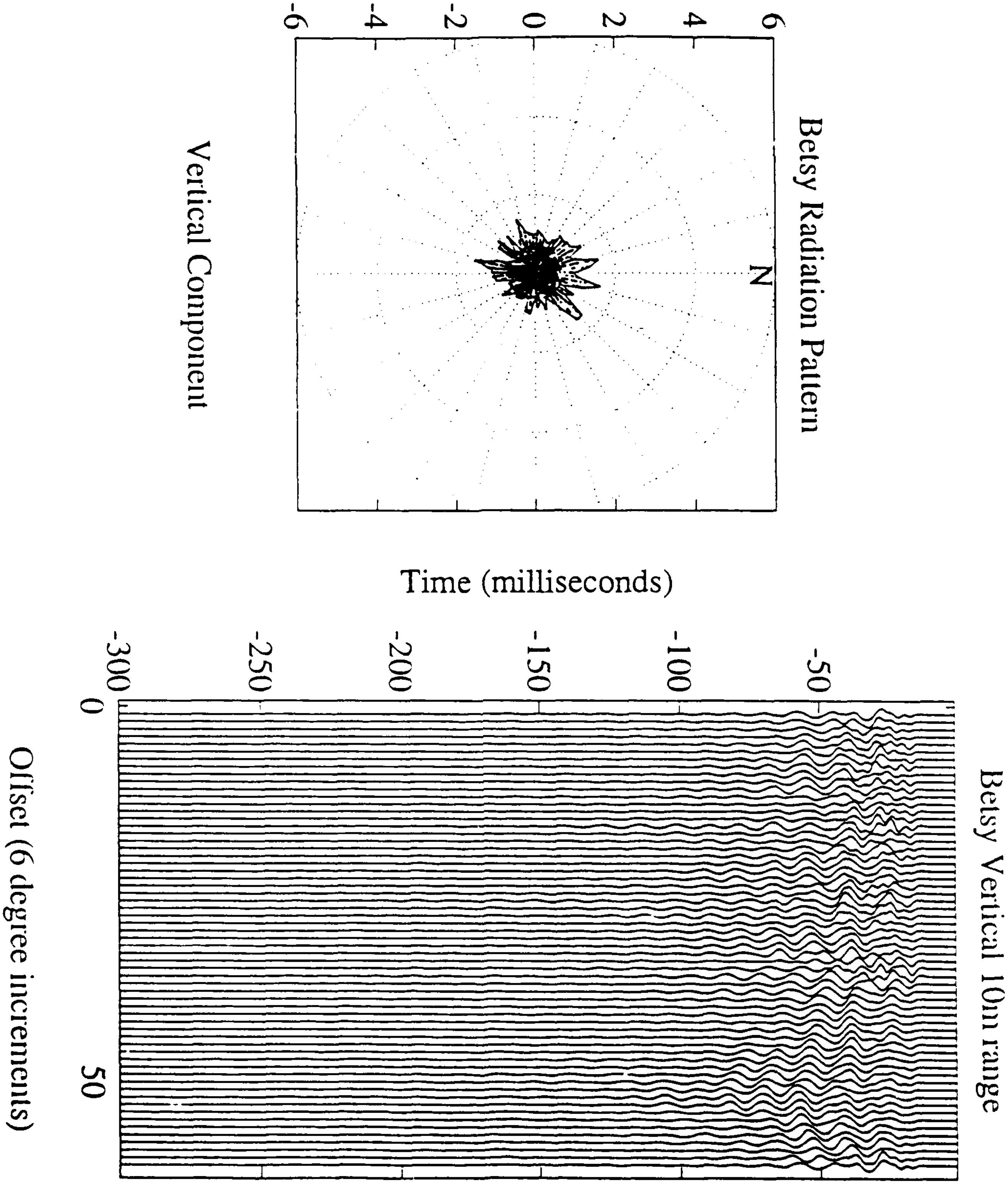


Figure 10a: Bottom panel consists of the 60 vertical velocity records recorded at 6° increments and 10m range from the Betsy Seisgun source at the McKinney, Tx test. Top panel is a polar plot of peak velocity.

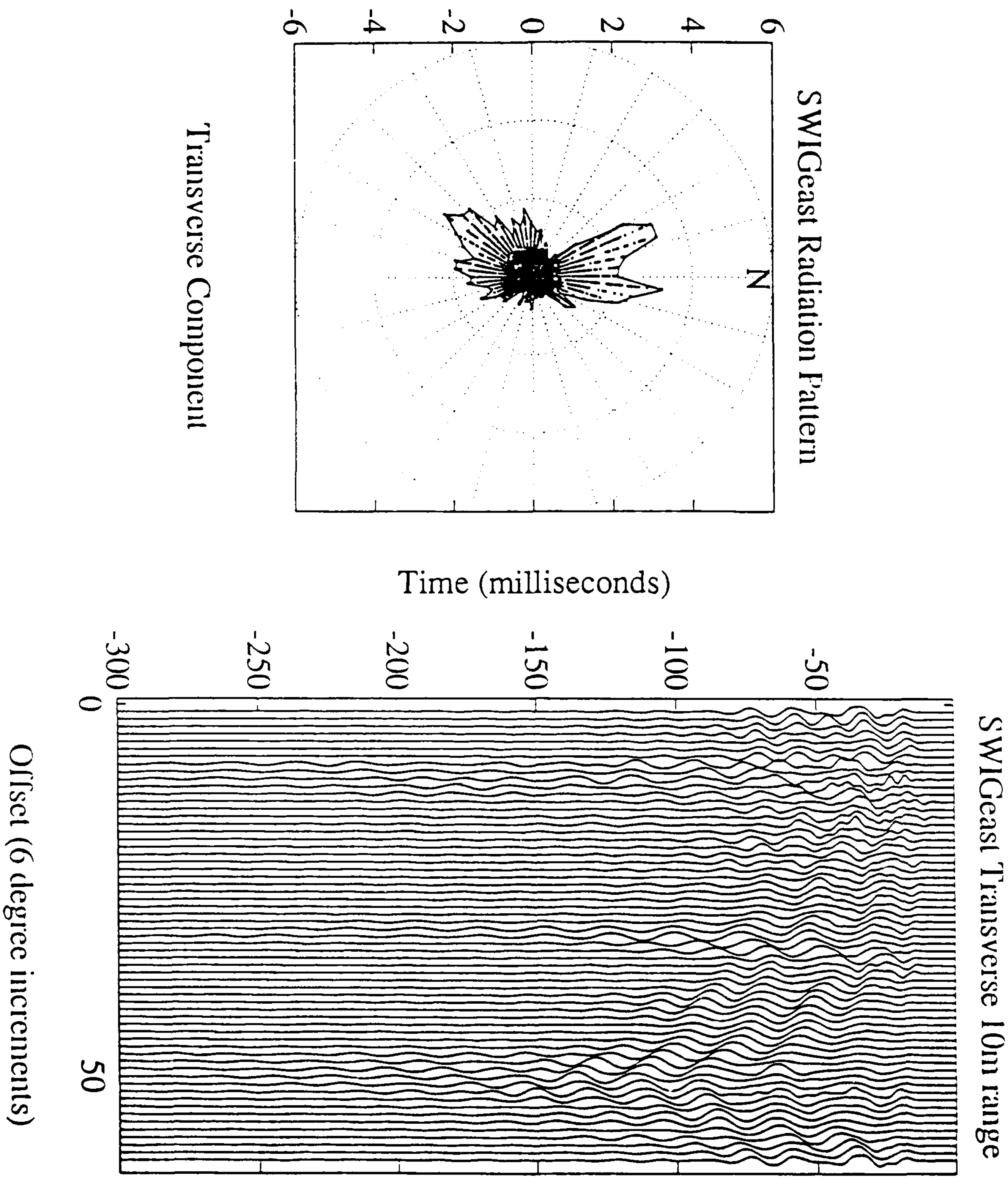


Figure 10b: Bottom panel consists of the 60 transverse velocity records recorded at 6^{o} increments and 10m range from the shear wave source at the McKinney, Tx test. Top panel is a polar plot of peak velocity.

dipolar radiation pattern is expected from theoretical grounds.

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